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ASPECTS ON THE EVALUATION METHOD OF DURABILITY ON BUILDINGS MADE IN CONCRETE STRUCTURES

BY

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Abstract. The paper presents the progress of the methods for assessing the durability of reinforced concrete structures, as well as modern design concept to sustainability. It highlights that the current requirements relating to sustainability can be satisfied to the extent that they are known factors that determine the state of degradation of the reinforced concrete, decisive measures to improve turning the physico-mechanical properties of materials and components.

Key words: concrete; durability; carbonation; chloride ions; cyclic freezing and thawing action.

1. Introduction

The durability of concrete or its ability to withstand the ravages of time and environment is as essential as the requirement that it must be strong enough to carry the intended loads and as such must be properly integrated at the initial stages of a building project (together with strength, stability, cost and buildability).

Concrete has been used as a construction material for more than a century. During this period of time, the concrete has undergone a continuous

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development, *e.g.* the growing use of secondary cementitious materials in the binding phase. Concrete with properties comparable to those properties of today's concrete has only been produced for a short time span, *i.e.* a couple of decades.

Today, it is not unusual to prescribe service lives of concrete structures up to 100 years even for heavily exposed structures. However, the durability of the concrete cannot be proved sufficiently by referring to experience, because experience with the actual material is limited to a much shorter period.

When it comes to concrete durability, engineers should not rely solely on specifying a minimum compressive strength, maximum water/cement ratio, minimum cementitious content and air entrainment. There are better ways to quantify durability. Low permeability and shrinkage are two performance characteristics of concrete that can prolong the service life of a structure that is subjected to severe exposure conditions.

But how should these properties be specified and measured? What should the acceptance criteria be?

The conventional design framework for concrete structures is primarily based on safety but currently focused on the aspects of durability. Under the conditions where problems on improper selections of used materials and mix proportion of concrete have arisen and some of the concrete structures are affected by hard deterioration actions in very severe environment, the durability of concrete structures surely be threatened to reduce its performance. Furthermore, it is obvious that environmental aspects should be also incorporated into the design of concrete structures. From an environmental viewpoint, it can generally be thought that life-extension of a structure is directly related to the reduction of environmental impact.

Consequently, the establishing of reasonable durability designs for concrete structures is very important, and now a day, many efforts have been made to evaluate the durability of concrete structures. In 2002, the JSCE Standard Specification for Concrete Structures (JSCE 2002) provided tools for verifying durability of concrete structures numerically, which was the first real code for the durability design in the world.

2. Present State of Durability Design

The severity of environmental, chemical and physical attacks on concrete depends on the properties of concrete and its exposure conditions. The actual deterioration phenomena of concrete structures include corrosion of reinforcement in concrete due to the ingress of chloride ions, carbonation of concrete, freezing and thawing, alkali–aggregate reaction, etc.

As the corrosion of reinforcement due to the ingress of chloride ions which are supplied from marine environment, use of deicing salt scattered on the road in the winter season, etc., is a typical and one of the most severe deterioration on concrete structures, it has been understood that concrete cover and its quality are the key and many efforts have been made to evaluate it quantitatively. The carbonation of concrete due to carbon dioxide has a disadvantage in reinforced concrete because the lower pH in carbonated concrete can not keep the passive condition on steel and introduces corrosion on the reinforcement. Freezing and thawing resistance can be secured by introducing an appropriate air-void system in concrete. The alkali–aggregate reaction can be prevented by several countermeasures such as the setting of threshold content of alkali in cement, the utilization of blast furnace slag and fly ash as mineral admixtures, etc. Nevertheless, most of the existing durability design codes do not provide a tool for evaluating the ingress of chloride ions in concrete, the carbonation of concrete and other deteriorations.

Durability design may be categorized into three levels as follows:

1° Prescriptive design.
2° Performance-type design.
3° Performance-based design.

In the prescriptive design for the durability of concrete, for example, the maximum water–cement ratio and minimum cement content are provided depending on the exposure conditions. At present, however, it is difficult to predict the durability performance of a structure directly throughout the lifespan because of the inadequacy of the models necessary for calculations. Further development of research on numerical approaches will pave the way to the realization of performance-based design. Under such current situations, what we can do to verify the durability in our codes is to introduce a "performance-type design" in which principal durability performance is considered with time. The JSCE 2002 provided such a design concept for durability design.

3. JSCE Standard Specification for Concrete Durability

3.1. General Concept

The performance of concrete structures has to remain the required one throughout its design service life. Conversely meaning, there will be no problems when utilized under a certain condition in which the required performance of the concrete structure is satisfied even if concrete or reinforcements partially deteriorate. This is a fundamental concept of the durability design that requires the performance verification of durability for concrete structures, not for concrete. In the durability verification of concrete structures in the JSCE Standard Specifications, this concept is also provided while the concept in the existing prescriptive durability design methods is completely different from it.

In the Specification, the performance verification methods for the deterioration of structure due to carbonation, the ingress of chloride ions, cyclic freezing and thawing action, chemical attack, and alkali aggregate reaction are stipulated as well as the verification method for water tightness and fire resistance of the structure are dealt with. In the following sections, these verification methods are described in detail.

3.2. Verification for Carbonation

As the carbon dioxide from the atmosphere penetrates into concrete, the pH in the cover concrete reduces. If such a zone of reduced pH reaches the location of the reinforcing bars in the concrete, they are rendered susceptible to corrosion. Once the corrosion is initiated, the formation and deposition of expansive corrosion products on the bars may cause the formation of longitudinal cracks along the reinforcing bars, which in turn could accelerate further corrosion and spalling of the cover concrete, and finally a significant reduction in the cross-section of the reinforcement. Therefore, it must be ensured in the durability design that the performance of the structure is not allowed to fall below the required level by the corrosion of the reinforcing bars. Based on this concept, to check that reinforcement corrosion due to carbonation in concrete does not occur, is comparatively easy and essentially on the conservative side. It is sufficient to verify that the depth of carbonation is less than the critical depth to initiate steel corrosion.

Consequently, the verification of a structure for carbonation is conducted by ensuring that

$$\gamma_i \frac{\gamma_d}{\gamma_{\lim}} \le 1.0, \tag{1}$$

where: γ_i is a factor representing the importance of the structure; in general, it may be taken as 1.0, but may be increased to 1.1 for important structures; $\gamma_{\lim} \le$ ≤ 1.0 – critical carbonation depth of steel corrosion initiation; $\gamma_d \le 1.0$ – design value of carbonation depth.

It is understood in general that corrosion of steel reinforcement may begin before the carbonation depth actually becomes equal to the cover thickness

$$\gamma_{\lim} = c - c_k \tag{2}$$

where: c is the expected value of cover thickness, [mm]; c_k – remaining non-carbonated cover thickness, [mm].

The remaining non-carbonated cover thickness is defined as a thickness of uncarbonated concrete still remaining in the neighborhood of the steel reinforcement even when the reinforcement corrosion just initiates, as shown in Fig. 1.

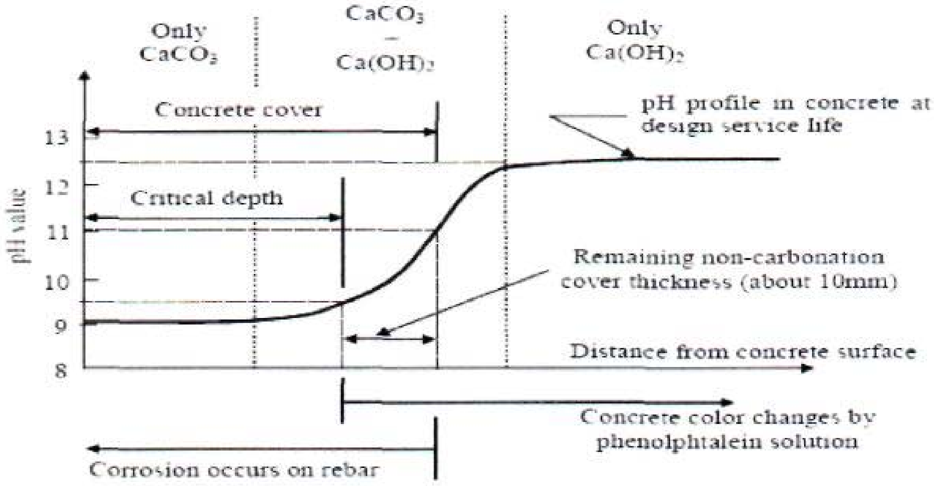

Fig. 1 – Schematic figure regarding the distribution in carbonated concrete.

Usually, there are indeed very rare cases in which corrosion is able to impair the performance of a structure having so long as the remaining non-carbonated cover was more than 10 mm. However, when chloride ions are present in concrete, corrosion may start even at larger remaining non-carbonated cover thickness (more than the 10mm) because the chloride ions can easily cause damage to the passivation film of the reinforcement in the condition having the high alkalinity. Therefore, in such cases, higher remaining non-carbonated cover thickness (*i.e.* 10…25 mm) is recommended. For estimating the depth of carbonation, the 'square-root' law (*i.e.* the depth of carbonation varies linearly with related to the square-root of time) is normally used, as it is considered to agree with previous studies and is easy to use. Design value of carbonation depth, therefore, may be obtained from eq.

$$\gamma_d = \gamma_{cd}\alpha_d\sqrt{t}, \tag{3}$$

where: α_d is the design carbonation rate; t – designed service life of structure; γ_{cb} – safety factor to account for the variation in the design value of carbonation depth.

In the JSCE Specification, the design carbonation rate α_d, is also given by eq.

$$\alpha_d = \alpha_k\beta_e\gamma_c, \tag{4}$$

where: α_d is the characteristic value of carbonation rate; β_e – coefficient representing the extent of environmental action; it may be taken as 1.0 for environments in which the surface of structure is difficult to be dried out, or for the north-facing surface; it may be increased to 1.6 for environments in which structures can be easily dried out or for the south-facing surface; γ_c – factor to account the material properties of concrete. In general it may be taken as 1.0, but should be taken as 1.3 for upper portions of the structure.

3.3. Verification for Reinforcement Corrosion Due to the Ingress of Chloride Ions

Chloride ions can easily penetrate into concrete from outer environment and produce the corrosion of steel reinforcements in concrete. In cases of the concrete structures in marine environment, the ones on which the deicing agents are used, and etc., it is very important to verify the reinforcement corrosion due to the ingress of chloride ions. As well as the matter mentioned in the clause of the verification for carbonation, if the structural performance does not appear to be impaired, it may still be considered serviceable even if there are some signs of reinforcement corrosion on the structure. In other words, the structural integrity of the structure may be considered to intact so long as corrosion induced longitudinal cracks are not formed along the reinforcing bars, even if there are some other signs of reinforcement corrosion. However, as far as the verification of the performance of a structure with respect to chloride penetration is concerned, a condition that chloride induced corrosion of the reinforcement should not occur during the service life of the structure, is relatively easy to understand and on the safe side. It may be sufficient to carry out to ensure during verification that the chloride ion concentration at the location of the reinforcement is below the critical concentration that could initiate corrosion in the reinforcement.

In the Standard Specification, therefore, the verification of a structure for reinforcement corrosion due to the ingress of chloride ions is conducted by ensuring that

$$\gamma_i \frac{C_{\lim}}{C_d} \leq 1.0, \tag{5}$$

where: γ_i is a factor representing the importance of the structure: in general, it may be taken as 1.0, but should be increased to 1.1 for important structures; $C_{\lim}$ – critical chloride concentration for initiation of steel corrosion; C_d – design value of chloride ion concentration at the depth of reinforcement.

The critical chloride concentration in the neighborhood of the reinforcement, which could initiate corrosion in the reinforcement, has been reported to be about 0.3…1.2 kg/m^3 of concrete by the past research works. For example, values of about 0.3…0.6 kg/m^3 have been reported from accelerated tests carried out with chlorides added to the fresh concrete, and values of 1.2…2.4 kg/m^3 from exposure tests carried out in the field. These differences in the critical chloride concentrations reported on the basis of accelerated and exposure tests, etc., can be attributed to factors such as differences in the water/cement ratio of the concrete, cover to the reinforcement, etc. The effect of high temperatures sometimes used in accelerated tests, can also influence conclusions.

Taking all the factors into account, the Specification sets a limit of 1.2 kg/m^3 (of chloride per cubic meter of concrete) as the critical chloride concentration, which can initiate reinforcement corrosion of which level is considered detrimental to the performance of the structure.

Mathematical formulations based on the diffusion theory are most commonly used to model chloride penetration in concrete. When using the eqs. based on the Fick's second law of diffusion to model, the design value of chloride ion concentration at the depth of reinforcement C_d is considered satisfactory, namely

$$C_d = \gamma_{\mathrm{cl}} C_0 \left[1 - \mathrm{erf}\left(\frac{0.1c}{2\sqrt{D_d t}} \right) \right], \tag{6}$$

where: C_0 is the assumed chloride ion concentration at concrete surface, [kg/m^3]; generally, it may be obtained from Table 2; c – expected value of concrete cover thickness, [mm]; in general, the designed cover thickness may be selected; t – design service life of the structure, [year]; γ_{cl} – safety factor, to account for the variation in the design value of the chloride ion concentration at the depth of reinforcement, C; normally, it may be set at 1.3, but in the case of high fluidity concrete, a value of 1.1 may be selected; D_d – design value of diffusion coefficient of chloride ions into concrete, [cm^2/year]; erf(…) – error function.

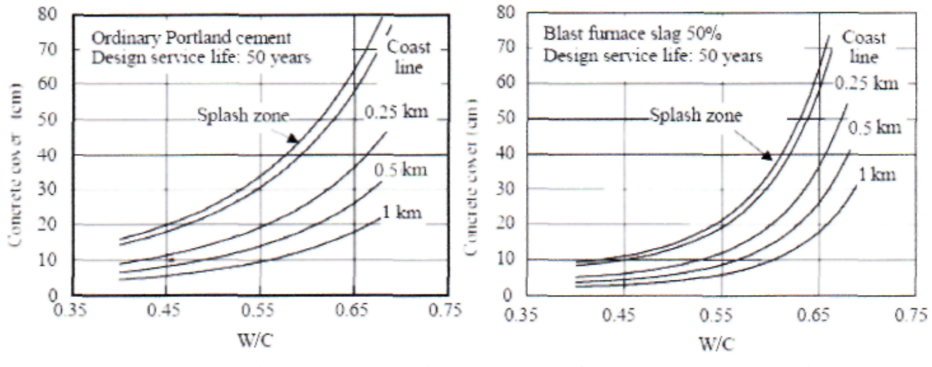

Fig. 2 – Minimum cover at different water/cement ratio required for concrete structure under chloride attack.

Fig. 2 shows the required minimum cover thickness at different water/cement ratios for concrete structures suffering from the chloride attack under 50 years of design service life.

3.4. Verification for Cyclic Freezing and Thawing Action

In cold regions, a cyclic freezing and thawing action is essential as representing the cause of deterioration of concrete structures, and raises pop-outs, scaling, and formation of micro cracks at the concrete surface. The degree of these damages of concrete structures depends not only on the quality of concrete but also on several other factors, such as the number of cycles of freezing and thawing actions, lowest temperature and the degree of water saturation of the concrete. However, up to now, virtually no quantitative information is available to relate these damages to any change in the performance of the structure under the freezing and thawing action. This means that it is difficult to specify a threshold level of 'allowable' deterioration and to utilize such the permissible level as indices or criteria for the verification of the required performance of the structures subjected to this action. Only a realistic manner is to be accepted to examine whether or not deterioration due to the freezing and thawing action is likely to occur in a structure, or how much degree of deterioration will progress inside concrete. In general, it can be considered that the structures will keep their required performance when the concrete has sufficient resistance to cyclic freezing and thawing action. Therefore, in the normal concrete structures under the action, a deterioration level in which some deterioration may occur on concrete but any degradation in the functions of the structure does not arise can be considered as a standard threshold level to keep the durability in structures.

The relationship between the results of the accelerated tests and the change in the level of performance in an actual structure subjected to cyclic freezing and thawing action is somewhat better understood on the basis of past research works and field data. It recommends that parameters such as the relative dynamic modulus of elasticity, which are measured in the accelerated tests, can be used as indices for the verification of the resistance of concrete to the action. Consequently, in the JSCE Specification, the verification of a structure for cyclic freezing and thawing action is conducted by ensuring that:

$$\gamma_i \frac{E_{\min}}{E_d} \le 1.0, \tag{7}$$

where: γ_i is a factor representing the importance of the structure; E_d – design value of relative dynamic modulus of elasticity; $E_{\min}$ – critical minimum value of relative dynamic modulus of elasticity to ensure required performance of the structure under cyclic freezing and thawing action.

3.5. Verification for Chemical Attack

When aggressive chemicals come in contact with or penetrate the concrete, they may react with the hydration products of cement causing dissolution of the concrete or formation of expansive products which causes cracking in concrete and is sometime followed by spalling of the cover concrete, etc. However, due to the limited understanding on how the deterioration of concrete under chemical attack results in the degradation of the structure performance, unfortunately quantitative evaluation has not been realized. Therefore, only conceptual provisions are introduced in the JSCE Specification for the verification of a structure for chemical attack.

The performance's degradation and the performance's change with time in the structure under the chemical attack are basically related to the change of the performances of the concrete itself as a constituent material. Thus, in order to ensure the durability of the structure under the chemical attack, it may be enough to ensure that the deterioration of concrete is kept below a certain pre-determined level (so as not to cause unacceptable levels of changes in the structural performance). It also be convenient and rational to actually set a certain level of chemical resistance in the concrete in order to preserve the integrity of the structure. Consequently, in case the concrete meets the criteria for resistance against chemical attack, the structure may be assumed that its performance will not be impaired on account of chemical attack.

In an actual verification for resistance to chemical attack in concrete, accelerated tests, exposure tests, or any other suitable tests shall be performed on concrete specimens at the conditions as close to the actual conditions as possible. Then, the verification should be carried in a manner to ensure that there is no notable deterioration of concrete on account of the chemical attack, or that the deterioration is confined to levels that do not significantly affect the performance of the structure.

When it is required that the deterioration of concrete is just within the level that does not affect the required performance of the structure, it is allowed in the specification to use the following maximum water/cement ratio, instead of the verification on the resistance to chemical attack of concrete directly:

a) When concrete is in contact with soil or water, which contain 0.2% or more sulfate such as SO_4, maximum water/cement ratio is 50%.

b) When deicing salts are used, maximum water/cement ratio is 45%.

When the chemical attack on the concrete is very severe, it may be difficult to secure the performance of the structure against chemical attack simply by increasing the concrete cover thickness and increasing the resistance of concrete. Certain sewer facilities and structures near hot springs could be examples of such concrete structures. In such cases, it may be more realistic and rational to recommend the use of corrosion resistant reinforcement materials and/or providing surface coating for the concrete.

4. Conclusions

In 2002, the JSCE Standard Specification was the first to provide a concept for durability design of concrete structures as a part of the performance-based design concept, while most of the existing design codes in the world have not yet provided such tools. This paper introduced the outline of the verification methods of the durability described in the Specification. However, the mentioned here method is not a final goal but the advanced method for predicting directly the durability performance of the structure throughout the lifespan is required for the realization of performance-based design.

Concrete structures and their components should be planned, designed, constructed, and operated, inspected, maintained and repaired in such a way that they maintain their required performance during their design lives with sufficient reliability for the safety and the intended use of the structure, under expected environmental conditions.

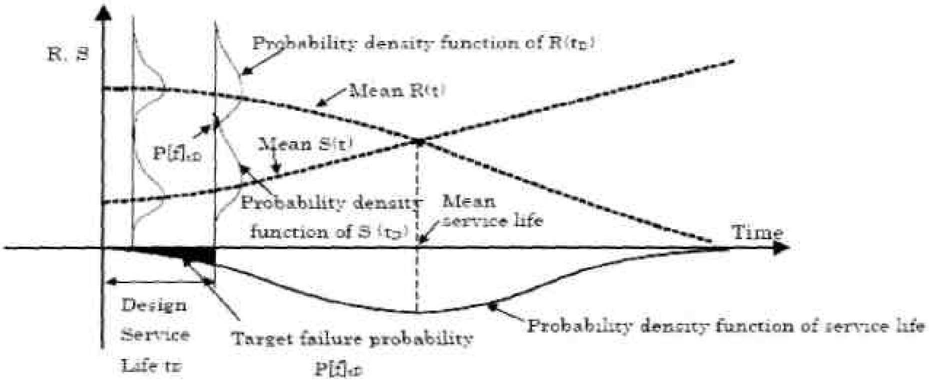

Fig. 3 – An example of mathematical model for predicting service life of structures.

As a result, the predicted service lives, t_s , of the structure and its components should meet or exceed their design lives, t_D; though t_s may be possible to be less than t_D for the components that are inspectable and replaceable. Fig. 3 shows one of the mathematical models for predicting the service life. In the model, the verification of the durability of the structure in the performance-based design concept is conducted ensured if inequalities

$$P\{f\}_{t_D} = P\{R(t_D) - S(t_D) \le 0\} \le P_{\text{target}}, \tag{8}$$

$$P\{f\}_{t_D} = P\{t_s - t_D\} \le P_{\text{target}}, \tag{9}$$

are satisfied, where: $R(t_D)$ is the resistance capacity of the structural component at the design life, t_D; $S(t_D)$ – cumulative degradation of the component at the design life, t_D; $P\{f\}_{t_D}$ – probability of failure in the designed structure at the design life, t_D; P_{target} – specified target probability.

The probability of failure in the designed structure in eq. (8) is indicated in Fig. 3 by the shaded overlap area of the probability density curves for $R(t)$ and $S(t)$ on a vertical axis, while the in eq. (9) indicated by the shaded area of the probability density function shown on the horizontal axis. For completion of this model, however, it is important that $R(t)$ and $S(t)$, which are the models evaluating the time-dependent behaviors in the performances of the structure and the progress of the degradation due to deterioration actions respectively, have to be developed as quantitative analysis models on the basis of the probability theory. There is no need to mention that concrete structures have contributed to the social and economic activities of human beings. On the other hand, civil engineering and building structures consume enormous resources and emit huge amount of greenhouse gases. Durability problems of concrete structures are directly linked to environmental impacts because the shortening of the lifespan will result in the wasteful utilization of limited natural resources. Thus, as regards the viewpoints not only of the safety of the structures in their service lives but also of the preservation of environmental conditions, it will become more important to improve durability design method.

REFERENCES

* * * *Guide to Durable Concrete*. ACI 201.2R-01, ACI Manual of Concrete Practice, Amer. Concr. Inst.

* * * *Concrete* – Part **1**: *Specification, Performance, Production and Conformity*. British Standard EN206-1, 2000.

* * * *Durability and Quality Control*. Eurocode 2.

* * * *Environmental Impact Evaluation of Concrete*. Japan Soc. of Civ. Eng., Concr. Engng. Series *62*, 2004.

* * * *General Principles on the Design of Structures for Durability*. ISO 13823 (WD), April 2005.

* * * *Concrete Durability Standards*. Concrete, **34**, *6*, 20.

ASPECTE ALE METODEI DE EVALUARE A DURABILITĂŢII A CLĂDIRILOR CU STRUCTURĂ DE BETON

(Rezumat)

Se prezintă stadiul în care se găsesc metodele de evaluare a durabilităţii structurilor din beton armat, precum şi conceptul modern de proiectare la durabilitate a construcţiilor. Se evidenţiază faptul că exigenţele actuale referitoare la durabilitate pot fi satisfăcute în măsura în care sunt cunoscuţi factorii ce determină starea de degradare a elementelor din beton armat, un rol hotărâtor revenind măsurilor ce urmăresc îmbunătăţirea caracteristicilor fizico-mecanice ale materialelor componente.